REMARKS

Claim 3 of the substitute specification filed herewith is canceled without prejudice. Claims 1 and 2 of the substitute specification are amended herein prior to receipt of a first office action.

Two new consecutive paragraphs are added to the substitute specification.

The amendments to the claims parallel amendments made to German patent application 102 38 061.9-52 by the German attorney's letter dated August 1, 2003. The present application is the U.S. national phase of International patent application PCT/EP03/07830 that claims Convention priority from such German application. The German Patent Office has indicated that such amended claims can be granted.

The paragraphs added to the substitute specification constitute English language translations of corresponding additions to the specification of the above-identified German patent application made by the German attorney's letter dated December 30, 2003.

No new matter is added by any of the amendments made herein.

Respectfully submitted,

Elliott N. Kramsky
Registration 27,812
Attorney for Applicant

10/524958

DT12 Rec'd PCT/PTO 18 FEB 2005

Title: METHOD FOR DETERMINATION OF AND COMPENSATION FOR THE SCALE FACTOR ERROR CAUSED BY CHANGES TO THE WAVELENGTH IN A GPS-SUPPORTED INS SYSTEM

Inventor: Manfred Krings

## BACKGROUND

### Field of the Invention:

The present invention relates to GPS-supported inertial attitude and heading reference (INS-Systems) systems having Kalman filters. More particularly, this invention pertains to a method for determination and compensation of scale factor error in such a system due to wavelength changes in multiple-axis fiber optic gyroscopes having a common light source. ~~The invention relates to a method for determination of and compensation for the scale factor error caused by changes in the wavelength in multiple axis fiver-optic gyroscopes (FOG) which are fed from a common light source, in a GPS-supported inertial track and attitude reference system (INS system) which is equipped with a Kalman correction filter.~~

### Description of the Prior Art

~~For~~ DE 196 51 543 C1 ~~discloses the~~ teaches subtraction of attitude and heading ~~track and attitude~~ angles produced by ~~means of the~~ a GPS receiver from the corresponding data supplied by an inertial sensor for iterative correction ~~assessment~~ of a platform calculation by means of a Kalman filter, in an attitude and heading ~~track and attitude~~ reference system including ~~with~~ an inertial system that is assisted by means of a GPS receiver. Such method obtains ~~order to obtain~~ an accurate ~~track/~~attitude/heading reference of comparatively wide bandwidth that is independent ~~independently~~ of acceleration

sensors. Correction models for GPS/INS mechanizations for ~~track and~~ attitude and heading reference systems in which ~~whose~~ INS values are corrected by ~~means of~~ a Kalman filter with different disturbance variables ~~also being considered~~ are ~~known from the published book~~ disclosed in Kayton and Fried, Avionics Navigation Systems, Second Edition (1997), pgs. 72-98.

~~In general~~ It is also generally known to estimate ~~for~~ the errors of inertial sensors (i.e., ~~the~~ zero error (bias), scale factor and axis alignment error) in INS/GPS systems ~~such as these to be estimated~~ with the aid of external information using a Kalman filter technique. Such ~~the possibility of~~ estimated values are then utilized to correct ~~used for correction of the~~ sensor data. Satellite navigation systems, such as the United States Global Positioning System ("GPS") are particularly suitable as ~~purpose since~~ they provide ~~the~~ position and ~~the~~ velocity virtually continuously, with high accuracy and without ~~any~~ drift. Kalman filters make it possible to use the difference between the position and velocity data from the GPS and ~~from~~ the inertial system to estimate ~~the~~ inertial sensor errors ~~of the, in order to~~ and to thoroughly perform ~~carry out an~~ appropriate corrections ~~correction~~.

However as mentioned above, the determination of ~~the~~ sensor errors with the aid of external assistance ~~information~~ and Kalman filter techniques, is dependent upon ~~on~~ a specific amount of motion dynamics of the vehicle (e.g. an aircraft) as error mechanisms of the inertial sensors can only be stimulated in this way. They ~~and~~ can then be observed via the Kalman filter.

~~In general, these~~ Such vehicles generally move in ~~on~~ a horizontal plane, with pitch and roll movements assuming relatively large values for only a short time ~~period~~. On the other hand, GPS reception is lost ~~entirely~~ during very major attitude angle changes (e.g. ~~when~~ aircraft ~~are~~ engaged in aerobatics) when the GPS antenna can no longer receive ~~the~~ satellite signals. As a result, the scale factor can then ~~now~~ no longer be estimated or determined satisfactorily. Furthermore, any increase in ~~the~~ scale factor error resulting from a change in the wavelength of the light source will become ~~becomes~~ evident only after the systems have been in use for a relatively long time.

The reduction in accuracy in ~~track/~~attitude/heading reference systems generally remains unknown as ~~unidentified, since~~ the system error is largely suppressed by vertical ~~sensor~~ and magnetic sensor assistance, and has therefore ~~thus~~ been found to be ~~technically~~ relatively insignificant. However, an improvement in ~~the~~ scale factor accuracy and ~~in~~ its long-term stability is absolutely essential for future tasks, particularly in assisted inertial navigation and when attitude angle accuracy is subject to stringent requirements.

SUMMARY AND OBJECTS OF THE INVENTION

It is therefore an object of the invention to provide ~~The invention is thus based on the object of providing~~ a method for improving ~~by means of which~~ scale factor accuracy, particularly for ~~in the case of~~ a GPS-supported inertial ~~track and~~ attitude and heading reference system ~~which is~~ equipped with a multiple axis fiber-optic gyroscope that is fed from a common light source.

The preceding object and others are addressed by the invention which provides ~~In the case of~~ a method for determining ~~determination of~~ the compensation for ~~the~~ scale error due to ~~caused by~~ changes in wavelength in multiple axis fiber-optic gyroscopes ("FOGs") fed from a common light source in a GPS-supported inertial ~~track and~~ attitude and heading reference system equipped with Kalman filter\ correction. Such method utilizes ~~the invention uses~~ the scale factor error determined for one axis with relatively fast motion dynamics ~~being used~~ as the Kalman filter correction value for the scale factor error correction for all the measurement axes of the FOG having ~~with~~ slower motion dynamics.

The preceding and other features of the invention will become further apparent from the detailed description that follows. Such description is accompanied by a set of drawing figures. Numerals of the drawing figures, corresponding to those of the written specification, point to the features of the invention with like numerals referring to like features throughout both the drawing figures and the written specification.
~~The invention and advantageous details will be explained in more detail in the following text, using one embodiment by way of example, and with reference to the drawings, in which:~~

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is ~~shows~~ a functional block diagram of an inertial navigation system, supported by GPS data and including ~~with~~ Kalman filter correction; and

Figure 2 is ~~shows~~ a ~~more~~ detailed functional block diagram for illustrating ~~in order to explain the~~ error correction, in particular scale factor correction, in accordance with ~~based on~~ the method of ~~according to~~ the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Figure 1 is a functional block diagram of an inertial navigation system, supported by GPS data and including Kalman filter correction. The scale factor of a fiber optic gyroscope ~~or fiber gyro~~ within an inertial navigation system 10 is governed predominantly by two factors. The Sagnac phase, which is produced by an external spin rate in the FOG (not illustrated), is governed by the wavelength (or frequency) of light in the glass fiber and ~~by~~ the geometric dimensions of the fiber coil (the area enclosed by the winding). ~~Furthermore~~ In a resetting system, the scaling of the reset (scaling: rotation angle increment/Sagnac phase) in the fiber gyro control loop governs the scale factor.

Figure 2 is a detailed functional block diagram for illustrating error correction, scale factor correction in particular, in accordance with the method of the invention. In ~~the case of~~ a multiple (e.g. three) axis FOG architecture 2 ~~(see Figure 2), which is~~ fed from a common light source 1, electrical scale factor is determined and monitored by an auxiliary control loop 3 of ~~in~~ the FOG electronics. On the other hand, scale factor error, which ~~that~~ is influenced by the geometric/mechanical dimensions of the FOG sensor coils, is recorded by ~~via~~ the system calibration (calibration data), and compensated for by means of a ~~an~~ FOG

error correction 4. The wavelength of the common light source 1 is ~~also~~ taken into account indirectly in such ~~this~~ system calibration and ~~Thus, in particular,~~ manufacturing errors are thus corrected. Changes in the wavelength of the common light source 1 during operation are no longer recorded. To this extent, the functional circuit diagram of Figure 1 illustrates the prior art, ~~which illustrates~~ an inertial navigation system 10 ~~that is~~ supported by a GPS navigation system 20 using a Kalman filter 30 in which ~~and whose~~ corrected navigation data on the output side is passed to a higher-level computer system.

The problems associated with ~~the~~ changes in scale factor that occur, for example, as a result of aging ~~effects~~ of the light source 1 are ~~, of course,~~ known. In the past, two relatively complex methods have been employed ~~used~~ to solve this problem. In the first method, a laser light source is utilized in which the spectrum required for FOG operation is produced by other ~~further~~ optical elements. ~~The primary expensive factor in this case is~~ The additional optical components add expense ~~as well as the fact that~~ while the lengths of fiber required is virtually twice as long as a result of ~~owing to~~ the longer wavelength of the ~~these~~ light sources. Another ~~proposed~~ option is direct measurement of the wavelength, making ~~which makes~~ it possible to compensate computationally for the associated scale factor error. The interferometric test layer ~~that is~~ required for this requires a number of additional optical and electrical components, again making ~~however, which make~~ the overall system considerably more expensive. No marketable and competitive solution employing ~~using~~ this option exists.

The invention makes use, inter alia, of the insight ~~discovery~~ that a change in the wavelength of the common light source 1 ~~which is~~ for all three measurement axes of a FOG triad has the same effect on all three measurement axes. This is based on the idea, in accordance with ~~according to~~ the invention, ~~specifically~~ of ~~also~~ employing the scale factor error of the vertical measurement axis z, which can be accurately determined, for the two horizontal measurement axes x, y of the fiber-optic system.

One advantageous embodiment of the invention takes additional account of the fact that the horizontal axes x and y constitute ~~are~~ the governing factor ~~on the determination~~ of the safety-critical attitude angles so that the scale factor error correction should only be carried out with a long time constant. In this case, it is important that the change in ~~the~~ wavelength and, thus, the increase in ~~the~~ scale factor error, be caused by aging of the light source over a period of several months. ~~Until now,~~ The precise relationship between the period of use and the wavelength shift ~~has admittedly~~ has not ~~yet~~ been previously investigated or statistically recorded. In addition to the time factor, ~~the~~ environment (temperature, vibration, etc) also exerts ~~has~~ a significant influence. When repairs are carried out, it has been necessary to replace light sources, or to recalibrate the system, after light source operating periods ~~times~~ of only 8 to 12 months. The time constant for correction of the Kalman filter should thus be in the range ~~between~~ 10 and 20 hours, with the most recently estimated error value used for each new flight. ~~The~~ Consideration of a long time constant is accordingly not problematic from the ~~safety view~~ point of view of safety as ~~since~~ only comparatively slow changes in

~~the~~ light wavelength need be expected.

Referring to Figure 2, the scale factors of the ~~these~~ axes x, y and z are corrected or compensated for, in addition to specific bias error terms, for all three measurement axes in the system block 31 in order to correct system errors in the Kalman filter 30, to be precise, considering only one previously determined scale factor error for the vertical measurement axis z. The corrected data is then passed, together with acceleration data for all three axes x, y, z, to the navigation calculation 6, and the result is fed back with the GPS navigation data to the Kalman filter 30.

The solutions and advantages of the invention can be summarized as follows:

1. In a GPS-supported inertial ~~track and~~ attitude and heading reference system having a number of FOG sensors ~~which are~~ fed from a common light source, any scale factor error is compensated uniformly for all measurement axes using a Kalman filter technique with the aid of system information obtained from a measurement axis which is subject to relatively fast dynamics.

2. This error correction is preferably used with a long term constant to prevent short-term disturbance in the supporting sensor (e.g. the FOG sensor) for a vertical axis, and the possibly associated erroneous estimates from corrupting the inertial system. In order to prevent an incorrect estimate of a Kalman filter from corrupting the system, it is advantageous to introduce a limit for the

correction, and to emit a warning or a maintenance demand upon reaching <u>such</u> limit.

3. In contrast to other possible known or proposed solutions, the invention achieves a reliable reduction of the scale factor error for complete FOG systems, without incurring additional hardware costs.

The invention is thus based on the observation and finding that, although the scale factor can be determined for the vertical measurement axis of a three-axis inertial ~~track and~~ attitude <u>and heading</u> reference system, it cannot be estimated satisfactorily for the horizontal measurement axes. This ~~admittedly~~ results in good accuracy in the case of track changes, although large attitude errors occur in the presence of large attitude angle changes. ~~These problems can be reliably overcome by means of the invention.~~ Thus, in one advantageous embodiment of the invention, the scale factor error determined for the vertical z axis in a three-axis ~~track and~~ attitude <u>and heading</u> reference system is used for scale factor error correction, for error compensation for the other measurement axes x, y.

The invention links the technical capabilities of the Kalman filter with a modern FOG technology to achieve better utilization and to provide considerably better compensation of scale factor for all three measurement axes.

<u>While the invention has been disclosed with reference to its presently-preferred embodiment, it is not limited thereto. Rather, it is limited only insofar as it is defined by the following set of patent claims and includes</u>

within its scope all equivalents thereof.

ABSTRACT

In a GPS-supported inertial ~~track and~~ attitude and heading reference system ~~which is~~ equipped with a Kalman correction filter ~~(30)~~ and ~~has~~ a multiple axis fiber optic gyroscope, the invention provides for only that scale factor error which is determined for the measurement axis (e.g. the vertical axis) ~~(z)~~ with relatively fast motion dynamics to be used as the Kalman filter correction value for the scale factor error correction for all the measurement axes ~~(x, y, z)~~ of the FOG ~~in order~~ to determine and compensate for the scale factor error caused by changes in the wavelength of a common light source ~~(1)~~. The ~~This~~ scale factor error correction is ~~advantageously~~ used only with a long time constant. ~~The invention ensures reliable correction for the scale factor for all measurement axes of the FOG system, to be precise without additional hardware complexity and only adaptation of the Kalman filter correction.~~